

Analysis of Eddy Current Capabilities for the Detection of Outer Diameter Stress
Corrosion Cracking in Small Bore Metallic Structures

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The use of eddy current techniques for the detection of outer diameter damage in tubing and many complex aerospace structures often requires the use of an inner diameter probe due to a lack of access to the outside of the part. In small bore structures the probe size and orientation are constrained by the inner diameter of the part, complicating the optimization of the inspection technique. Detection of flaws through a significant remaining wall thickness becomes limited not only by the standard depth of penetration, but also geometrical aspects of the probe. Recently, an orthogonal eddy current probe was developed for detection of such flaws in Space Shuttle Primary Reaction Control System (PRCS) Thrusters. In this case, the detection of deeply buried stress corrosion cracking by an inner diameter eddy current probe was sought. Probe optimization was performed based upon the limiting spatial dimensions, flaw orientation, and required detection sensitivity. Analysis of the probe/flaw interaction was performed through the use of finite and boundary element modeling techniques. Experimental data for the flaw detection capabilities, including a probability of detection study, will be presented along with the simulation data. The results of this work have led to the successful deployment of an inspection system for the detection of stress corrosion cracking in Space Shuttle Primary Reaction Control System (PRCS) Thrusters.

ANALYSIS OF EDDY CURRENT CAPABILITIES FOR THE DETECTION OF OUTER DIAMETER CRACKING IN SMALL BORE METALLIC STRUCTURES

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ABSTRACT. The use of eddy current techniques for the detection of outer diameter damage in tubing and many complex aerospace structures often requires the use of an inner diameter probe due to a lack of access to the outside of the part. In small bore structures the probe size and orientation are constrained by the inner diameter of the part, complicating the optimization of the inspection technique. Detection of flaws through a significant remaining wall thickness becomes limited not only by the standard depth of penetration, but also geometrical aspects of the probe. Recently, an orthogonal eddy current probe was developed for detection of such flaws in space shuttle primary reaction control system (PRCS) thrusters. In this case, the detection of deeply buried intergranular cracking by an inner diameter eddy current probe was sought. Probe optimization was performed based upon the limiting spatial dimensions, flaw orientation, and required detection sensitivity. Analysis of the probe/flaw interaction was performed through the use of finite element modeling techniques. Experimental data for the flaw detection capabilities, including a probability of detection study, will be presented along with the simulation data. The results of this work have led to the successful deployment of an inspection system for the detection of intergranular cracking in PRCS thrusters.

Keywords: Eddy Current, ID Probe, Reaction Control System Thrusters, Space Shuttle

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INTRODUCTION

Nondestructive evaluation of complex aerospace structures often requires sensor deployment in physically constrained regions. One such example is inside diameter inspection of tubing or bore holes. Due to access limitations, sensor deployment into the inside diameter of the part may be the only viable inspection option, even for flaws originating on the outside diameter of the structure. As the distance of the flaw from the inside diameter approaches the radius of the bore, probe size limitations can have a significant effect on the probability of detection of the defect. For eddy current techniques, probe size and orientation become a significant factor affecting the depth of penetration of the electromagnetic field into the part. In this work the effect of probe orientation on the depth of penetration of the electromagnetic field will be explored and applied to the development of an inspection technique for space shuttle primary reaction control system (PRCS) thrusters. The developed system for the detection of outer diameter intergranular cracking in PRCS thrusters will be presented along with inspection results, including probability of detection testing.

EDDY CURRENT INSPECTION OF SMALL BORE STRUCTURES

The application of eddy current techniques for the detection of outer diameter damage in tubing and other complex aerospace structures often requires the use of an inner diameter probe due to a lack of access to the outside of the part. In small bore structures, the probe size and orientation are limited by the part inner diameter and can become the dominating factors controlling the depth of penetration of the field into the part under test. The commonly used skin depth equation,

$$B_x / B_0 = e^{-x/\delta}, \quad \delta = 1/\sqrt{\pi f \mu \sigma}, \quad (1)$$

can overestimate B_x , the field strength at distance x beneath the surface. In equation (1), δ = the standard depth of penetration, f = excitation frequency, μ = permeability, and σ = electrical conductivity [1]. Equation (1) is calculated based upon a uniform plane wave over a conducting half space and thus ignores all probe size effects. For a small diameter probe operating at a low frequency the field diffusion into the part can become constrained by the dipolar decay of the field along the axis of a circular current loop. This is given as

$$B_x / B_0 = r^2 / (r^2 + x^2)^{3/2}, \quad (2)$$

where r = radius of the current loop [2]. Figure 1 shows the normalized field strength versus distance from the coil for various coil radii and compares these results with the standard eddy current depth of penetration (1). For coil radii near $\delta/2$ the dipolar field decay (2) dominates the standard depth of penetration (1) at distances from the coil greater than approximately 0.2δ .

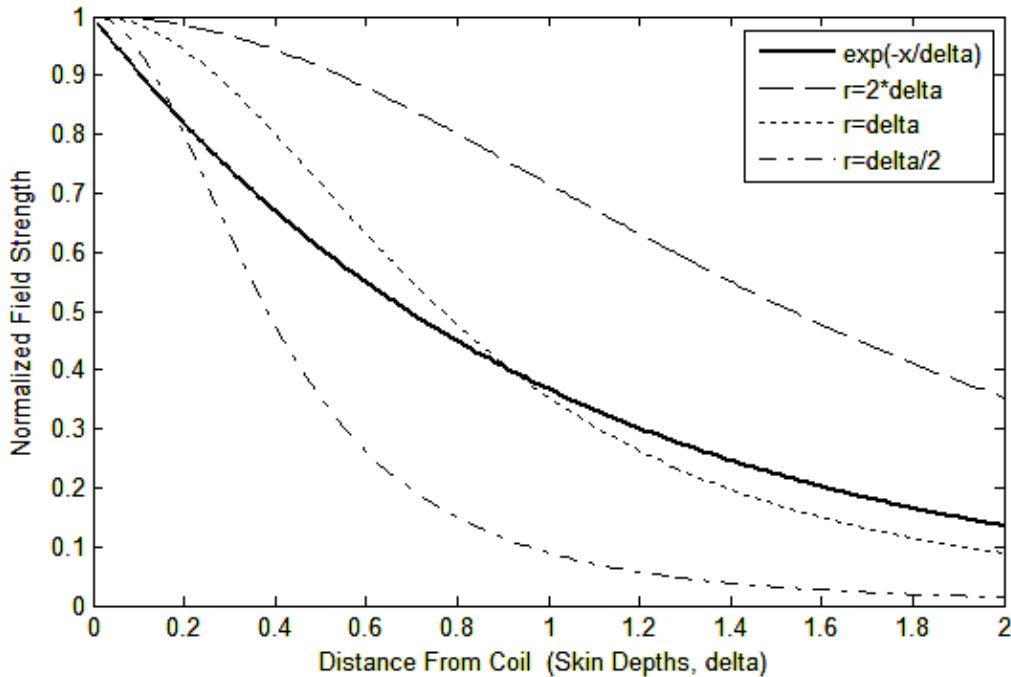


FIGURE 1. Comparison of standard eddy current depth of penetration with dipolar field decay for small radius coils.

The eddy current penetration depth into small bore structures can be somewhat improved from the dipole limiting case of equation (2) through appropriate probe orientation and design. As discussed above, the dipole decay is associated with field intensity along the axis of a current loop. This is appropriate for the typical probe orientation of the coil positioned normal to the surface to be inspected. Rotating the probe 90 degrees into a tangential inspection mode will more closely approximate the plane wave solution from which equation (1) is derived and result in a decreased rate of decay of the field strength with distance into the material under test. This is illustrated in Figure 2 which displays a finite element solution for the normalized eddy current density for the two probe orientations. Figure 3 plots the eddy current density versus depth into the part at a location directly under the coil windings. This plot shows that a higher current density near the surface and a faster rate of decay with depth occurs for the probe oriented normal to the part. While beneficial for the detection of surface breaking flaws, high surface current densities do not aid in the detection of deeply buried flaws and can increase signal noise due to larger lift-off and probe wobble effects. Probe and part dimensions, lift-off, drive currents and operating frequencies were held constant for the two simulations.

APPLICATION TO SPACE SHUTTLE PRIMARY REACTION CONTROL SYSTEM THRUSTERS

A direct application of the ideas discussed above can be found in the recently developed eddy current system for detection of deeply buried cracking in space shuttle primary reaction control system (PRCS) thrusters [3]. The discovery of intergranular cracking in the PRCS thrusters was identified as a potential failure mechanism of the critical flight hardware and triggered an extensive NDE effort to identify techniques capable of detecting the potential damage [4-6]. Although the cracking initiation site was determined to be an outer diameter relief radius, the outer surface of the thruster is inaccessible without extensive disassembly of the hardware. As such an interior inspection technique down the nozzle of the thruster and into a small bore acoustic cavity was required. Figure 4 displays a cut-away view of the thruster along with the eddy current sensor designed for the inspection. The sensor incorporates matched eddy current coils arranged orthogonally to each. The inspection coil (on the left in the thruster cut-away view) is arranged with its axis along the circumferential direction (tangential inspection). As discussed above this orientation enables a relatively deep field penetration with the small diameter coil required to fit into the acoustic cavity. The orientation also induces

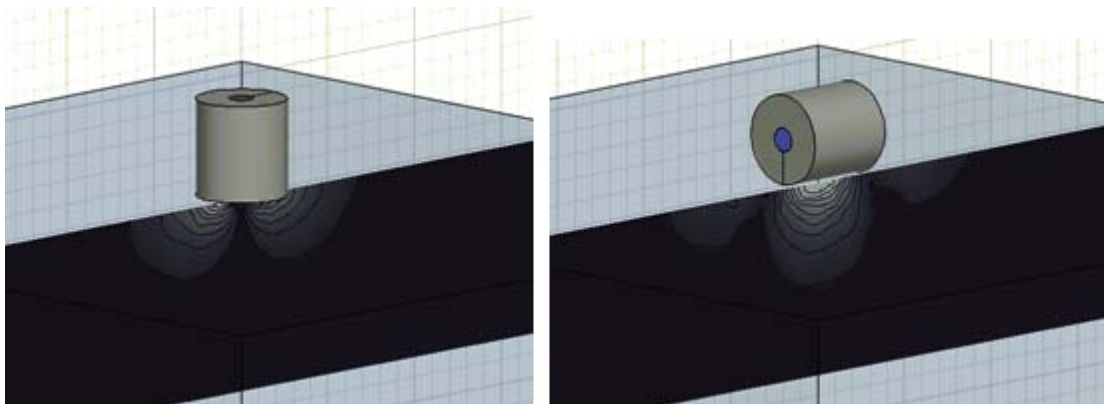


FIGURE 2. Finite element simulations for normalized eddy current density calculated for normal and tangential probe orientations.

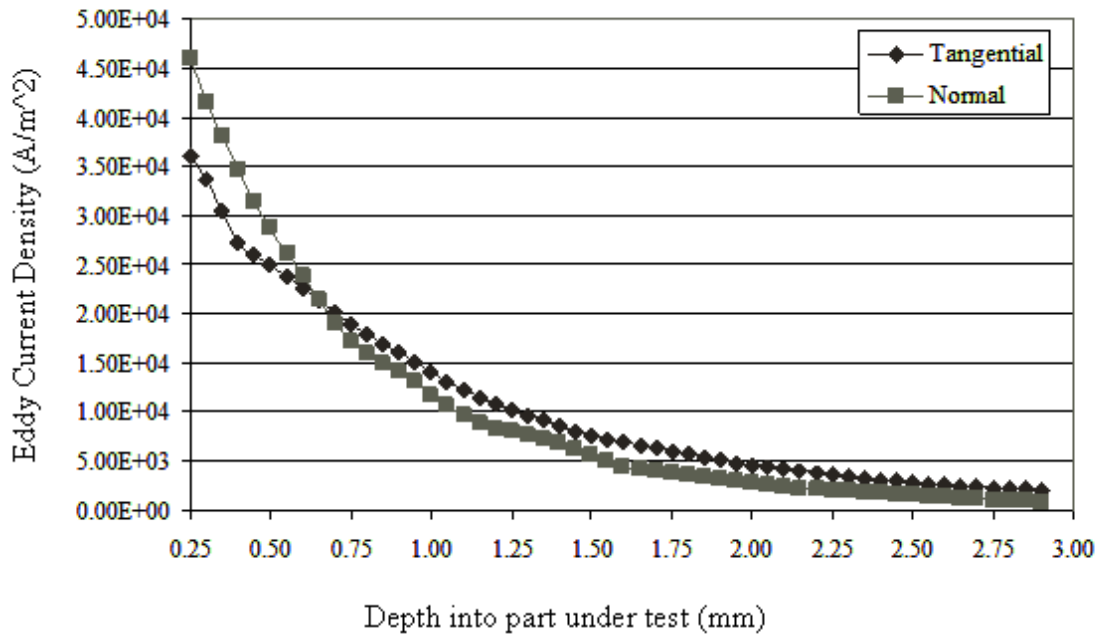


FIGURE 3. Calculated eddy current density versus depth for an inspection coil oriented with its axis either normal or tangential to the part under test.

current in a direction that will have a strong interaction with cracking originating in the relief radius and growing towards the acoustic cavity. A second coil is arranged with its axis parallel to the axis of the acoustic cavity. This second coil is designed to provide a local reference for the inspection coil while minimally interacting with damage originating at the relief radius. Inspections are performed by scanning the eddy current coils inside the acoustic cavity through the region identified as susceptible to intergranular cracking. The developed inspection procedure incorporates a dual frequency excitation, with the lower frequency enabling deep penetration into the part and the upper frequency helping to cancel out responses from surface features such as lift-off and roughness of the acoustic cavity wall.

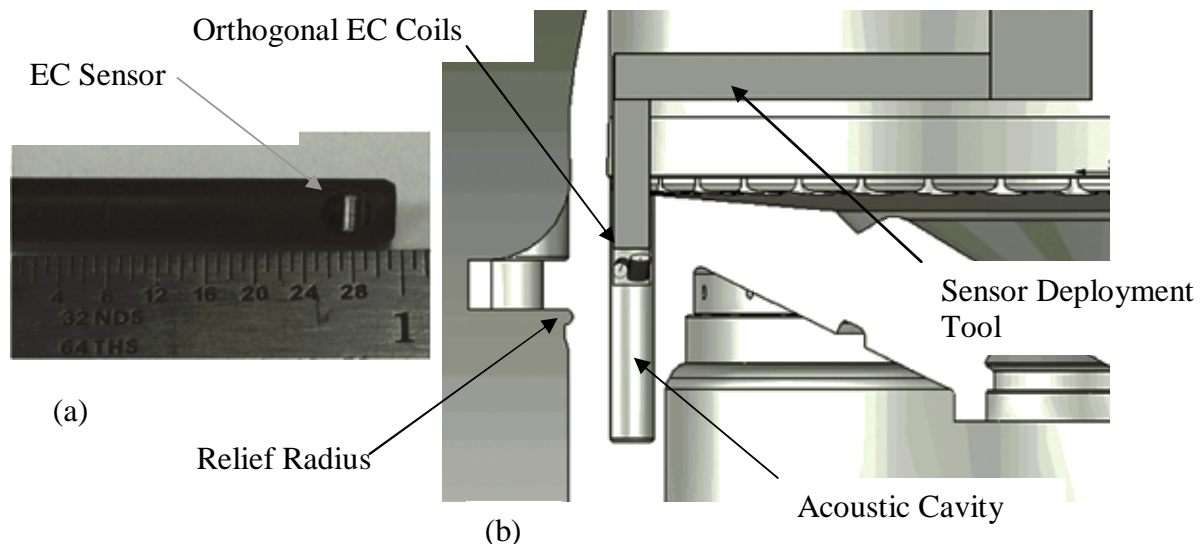


FIGURE 4. Photograph of prototype eddy current sensor (a) and schematic diagram of eddy current thruster inspection tool (b).

Figure 5 shows a close up view of the front panel of the system software with data acquired during an inspection of a notched reference standard with 0.020" remaining wall thickness between the notch and the acoustic cavity. The system control and data processing software initiates a scan sequence by sending a trigger signal to the stepper motor. Analog output data from the eddy current instrument are then acquired by the computer as the sensor scans partially out of and then back into the acoustic cavity. After the scan completes, the acquired data at 12 kHz, 100 kHz, and frequency mix (calculated as the difference between the 12 kHz and 100 kHz responses) are displayed. The three plots from left to right across the screen display the 12 kHz, 100 kHz, and frequency mix results, respectively. The nearly through-wall flaw is clearly detected in the low frequency and mix signals, with a slight indication of the flaw apparent even at 100 kHz. Toggle and slide switches are incorporated to enable the plotting of data over any region within the complete scan range, as well as of data acquired during the outgoing or ingoing scan of the probe. Controls are also present to adjust the mix signal parameters for data analysis on the selected portion of the scan data. The front panel also contains a micrograph of an intergranular cracking site dissected from a PRCS thruster. The typical crack profile displayed in the micrograph is useful for interpreting the eddy current response in relationship to potential damage in the hardware. A final feature to be noted on the front panel is the calculated "Indication Strength", given in the upper right hand corner of the display. This value is calculated by fitting the eddy current response to the anticipated profile for the sensor scanned through an unflawed acoustic cavity region and is discussed in detail in a previous report [3].

VALIDATION AND PROBABILITY OF DETECTION TESTING

In order to verify the reliability of the eddy current inspection system, an extensive validation including over 1500 blind inspections was performed [7]. This validation testing was conducted at United Space Alliance (USA) facilities in Cape Canaveral Air Force Station by USA eddy current level II NDE inspectors. Prior to the beginning of the inspections, two days of training consisting of a system overview, demonstration, and

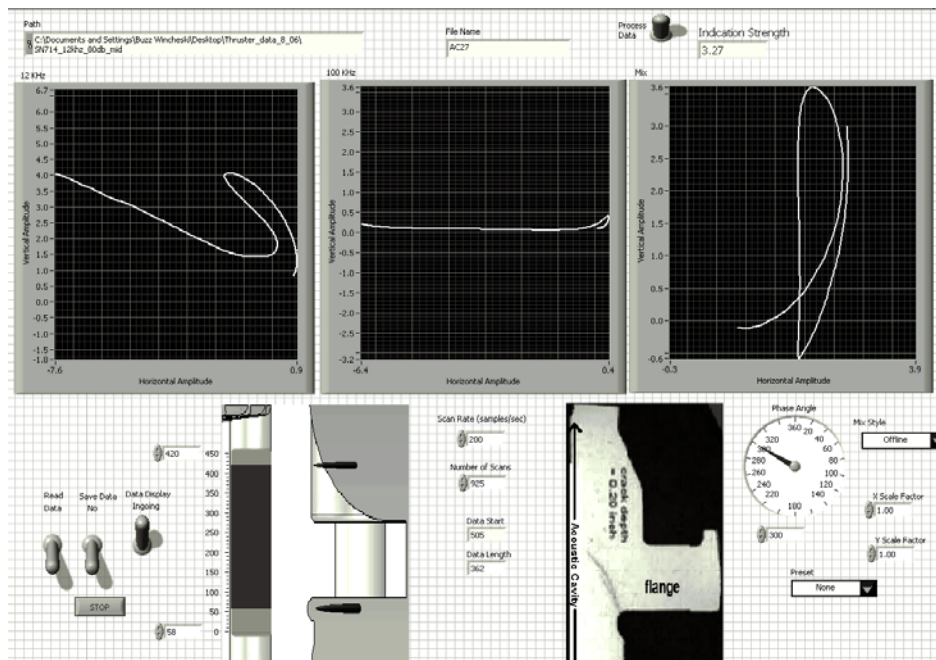


FIGURE 5. Front panel display of system control and data processing software.

hands on practice was provided to the inspectors. The validation inspections were performed in accordance with written procedures documented in a validation plan [8, 9]. Flaw calls were made immediately by the inspectors based upon the reported indication strength. Inspection results were documented on inspection reports and raw data saved for further analysis.

Four PRCS thrusters, three of which contained fabricated electric discharge machine (EDM) notches, were used for the validation study. Each sample was inspected three times by each of three inspectors for a total of nine inspections for each site. Notches were placed either directly across from a single acoustic cavity or between adjacent cavities at 18 total locations. The remaining wall thickness between each fabricated flaw and the nearest acoustic cavity was between 0.020" and 0.060". Figure 6 displays the inspection results for one of the validation test samples. The plot shows the indication strength versus acoustic cavity number for each of the 42 cavities in the thruster. The six fabricated flaws in the thruster are clearly evident above the background of the unflawed cavities. The flaws placed between cavities are detected at the two cavities bounding the flaw (acoustic cavities 5-6 and 10-11) while those placed directly across from a single cavity show a single peak at that cavity (cavities 16, 27, 32, and 37). By procedure a threshold was set at an indication strength of 0.5 volts to discriminate flawed from unflawed cavities. Data from all nine inspection cycles are plotted and show the excellent reproducibility of the system.

In analyzing the validation testing results it was found that system response to flaws was somewhat lower for notches placed between cavities. This can be understood based upon the orientation of the sensor within the cavity. As shown in Figure 4, the tangentially oriented coil is directed radially outward toward the relief radius. Flaws originating in front of the cavity will approach the sensor from the center of the coil while those originating between cavities will approach from one of the ends of the coil. The induced current density of the tangential coil is highest in the center of the coil, as shown in Figure 2, so the greatest sensitivity is expected to be in that direction. All naturally occurring

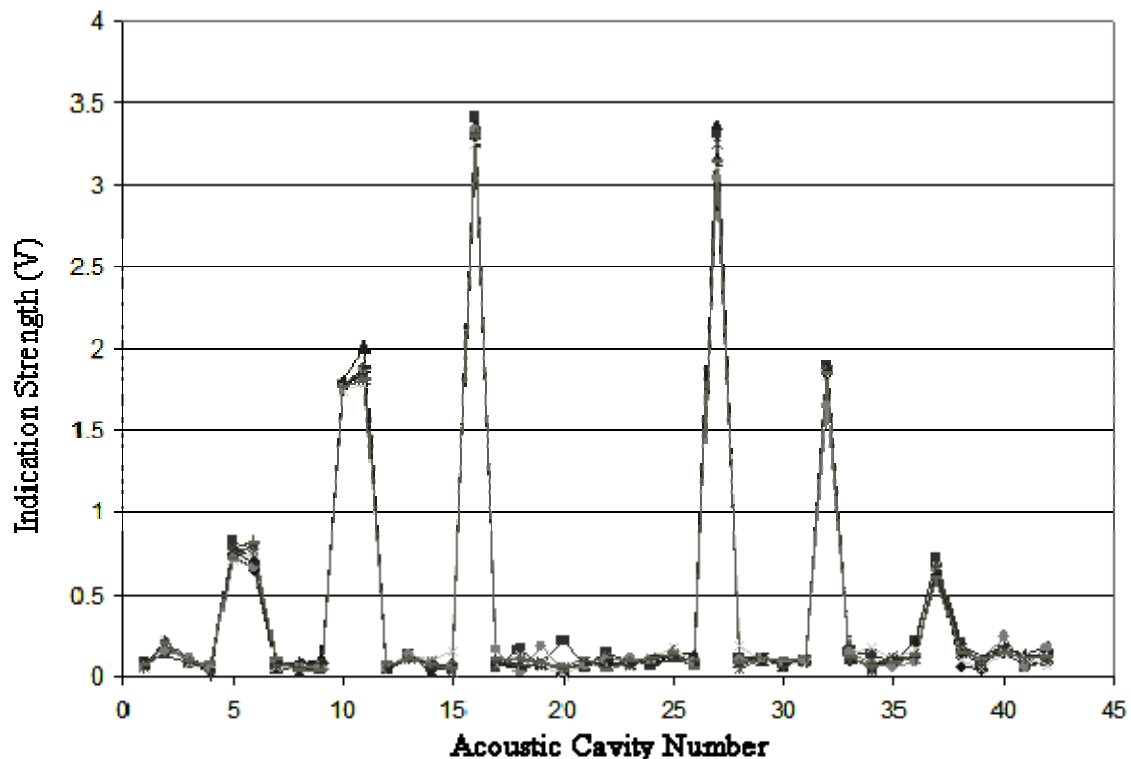


FIGURE 6. System response to fabricated defects in one of the validation test articles.

damage identified to date, however, has shown a very high aspect ratio of crack length to crack depth [6]. The naturally occurring flaw aspect ratio thus minimizes the potential for deep cracking between acoustic cavities without appreciable damage directly in front of a single cavity. A slight drop off in system sensitivity was also seen for flaws approaching the acoustic cavity at a steep angle. In this orientation edge effects associated with the proximity of the flaw tip to the thruster face have been determined to be responsible for the slightly reduced detection sensitivity [3, 7]. It should be noted that such high angle flaws appear to be rare. Destructive analysis performed by the NASA Engineering and Safety Center on PRCS Thruster S/N 132 found flaw angles to be typically between 40 and 50 degrees with a maximum measured flaw angle of 54 degrees [6].

A detailed probability of detection analysis of the validation data has been performed by Sandia National Laboratories to quantify the system capabilities and reliability [10]. The results show that, for the most likely orientation of naturally occurring damage, flaws with a remaining wall thickness of 0.060" have 90% detectability with 95% confidence. The false call rate was estimated to be below 0.0023 (no false calls were reported in the validation study). Due to the slow crack growth rates in this area the reported 90/95 levels provide a large safety margin for continued operation of the critical shuttle hardware. A separate probability of detection curve was generated for the worst case scenario, high angle flaws isolated to locations between acoustic cavities. Although such flaws have a very low likelihood of occurrence, the 90/95 flaw length of 0.039" remaining wall thickness still provides a positive margin for continued safe use of the hardware.

SUMMARY

The nondestructive evaluation of critical aerospace components often requires sensor deployment into physically constrained areas. Eddy current sensors are often used to facilitate such inspections due to the relative ease of fabrication of small eddy current coils and the ability to operate without couplants. In cases where a subsurface detection is required however, the effect of the probe size and orientation on the depth of penetration of the electromagnetic field must be considered. The eddy current skin depth equation, based upon an electromagnetic plane wave interrogation, can significantly overestimate the depth of penetration of the induced current into the part under test. In this work the depth of penetration of an alternative probe design, based upon a tangential coil orientation to the part under test, has been compared to a normally oriented surface probe inspection. Analytic and finite element modeling has been performed and has shown improved subsurface interrogation capabilities.

Intergranular cracking in space shuttle primary reaction control system thrusters has been presented as an example of a deep flaw detection requirement in a physically constrained area. To meet the inspection requirements, an eddy current system was developed utilizing a tangential inspection coil. Validation testing was performed and found that intergranular cracking originating on the external surface could be reliably detected with an inside diameter small bore eddy current coil. Results showed that cracking progressing to within 0.060" of the inner diameter inspection surface could be detected at 90% probability of detection with 95% confidence.

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